THE EFFECT OF RESIDUAL STRESS ON CRACK PROPAGATION IN HY-80 STEELS

by

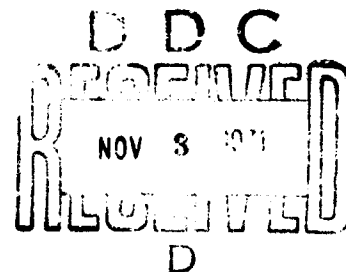**Robert Sherman**

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13. ABSTRACT

Tests were conducted to determine the effect of residual stress on the rate of crack growth in HY-80 plate steel. A residual stress field, over and above that inherently present in as-quenched and tempered material, was induced by means of welding-in of a pre-cracked patch plate into the specimen body; a cyclic load, which would induce particular values of stress intensity, was then applied. From the ensueing test results, a growth rate relation was determined and compared to a similar relation obtained from like tests performed on specimens having zero weld-induced residual stress.

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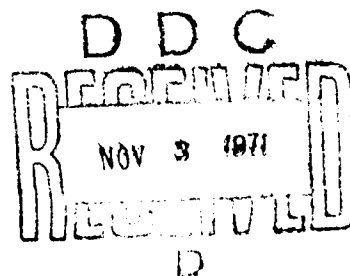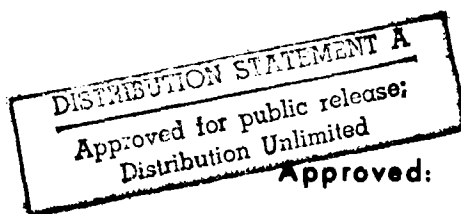# THE EFFECT OF RESIDUAL STRESS ON CRACK PROPAGATION IN HY-80 STEELS

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Details of illustrations in
this document may be better
studied on microfiche

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Robert C. DeHart, Director
Department of Structural Research

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I. INTRODUCTION

This report presents the results of tests performed to determine the influence of residual stress on the rate of crack growth in as-quenched and tempered HY-80 plate steels.

Two specimen configurations were tested. One contained weld-induced residual stresses at the tip of a fatigue crack approximately equal to the yield strength of the material and the other, a fatigue crack free of any weld-induced stress. For both configurations, the fatigue crack was generated mechanically at the end of a torched and sawed edge notch. The crack was then propagated across the specimen by means of a pull-release action effected with a hydraulic cylinder installed in a manner so as to apply a pure axial tension.

II.   TEST MATERIAL

The material used in this investigation was taken from a 3/4-inch thick HY-80 plate produced by Lukens Steel Company. The chemical analysis and mechanical properties, as developed from water quenching from 1625/1675°F and tempering at 1100°F, minimum, follow below. Additionally, Figures 1 and 2 are photographs of the microstructure, along and across the grain direction, respectively.

1.   Chemical Analysis

Element	%	Element	%
C	0.17	Ni	2.25
Mn	0.29	Cr	1.30
P	0.010	Mo	0.25
S	0.015	V	0.003
Cu	0.15	Ti	0.003
Si	0.22		

2.   Mechanical Properties

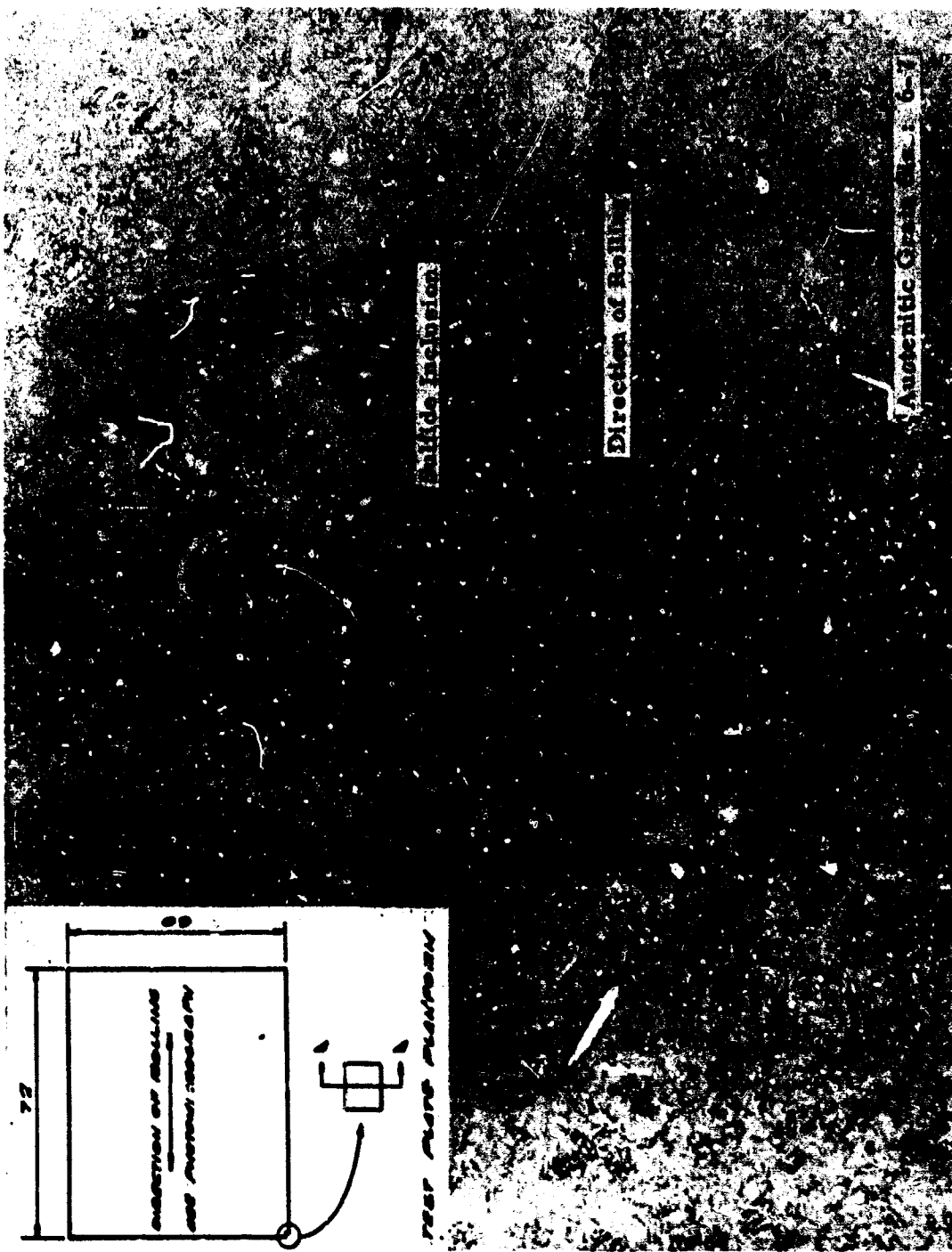|	
Tensile strength:	106,000 psi
Yield strength:	88,950 psi
% Elong. in 2-inches:	25.5
% R.A.:	69.2
Charpy V-notch @ -120°F:	130 ft lbs
Brinell hardness:	228

FIGURE 1. PHOTOMICROGRAPH OF THE LONGITUDINAL SECTION A-A

FIGURE 2. PHOTOMICROGRAPH OF THE TRANSVERSE SECTION A-A

III.   TEST SPECIMEN AND TEST SET-UP

The specimen was fabricated by introducing, into a patch plate, a fatigue crack at the tip of a torched plus saw-sharpened slot; the patch plate was then welded into the specimen body.   This is shown in Figures 3 and 4.   Therein, it will be noted that in the "A" configuration patch, a stress near the crack tip will not be induced as a result of cooling - and accompanying shrinkage - of the weld because no restraint is offered by the specimen geometry; in the "B" configuration, however, restraint is offered by the specimen body and, as cooling progresses, tensile stresses are induced across the patch, normal to the fatigue crack.

After initiation and propagation of the fatigue crack into the patch plate for a distance of 1/2-inch approximately, strain gages with axes parallel to the specimen axis were affixed on both sides of the specimen, adjacent to the crack tip.   These gages served a dual purpose in that they were used to monitor strains induced by welding and, also, to detect any tendency for transverse bending due to side-to-side eccentricity of the later applied load.   Because of the proximity of the gages to the weld area, Micro-Measurements, Inc. high temperature type gages were used.   The instrumented specimen was then mounted in the loading frame shown in the photograph, Figure 5.   This loading fixture incorporated an 8-inch diameter hydraulic cylinder attached to a lever beam which had a mechanical advantage of 3. 35:1.   As all joints were pinned, (see Figure 5), the
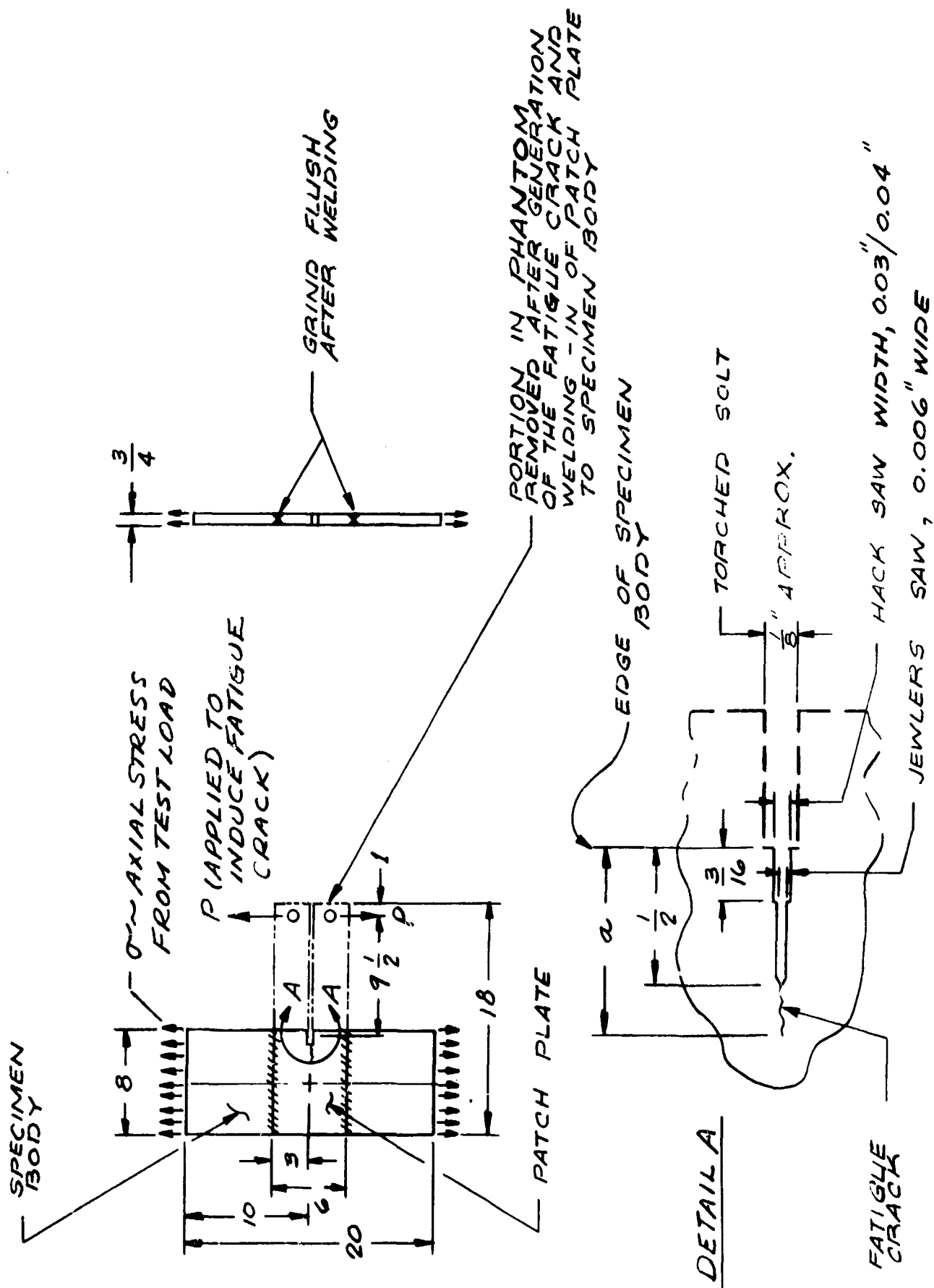
FIGURE 3.   SPECIMEN CONFIGURATION "A"
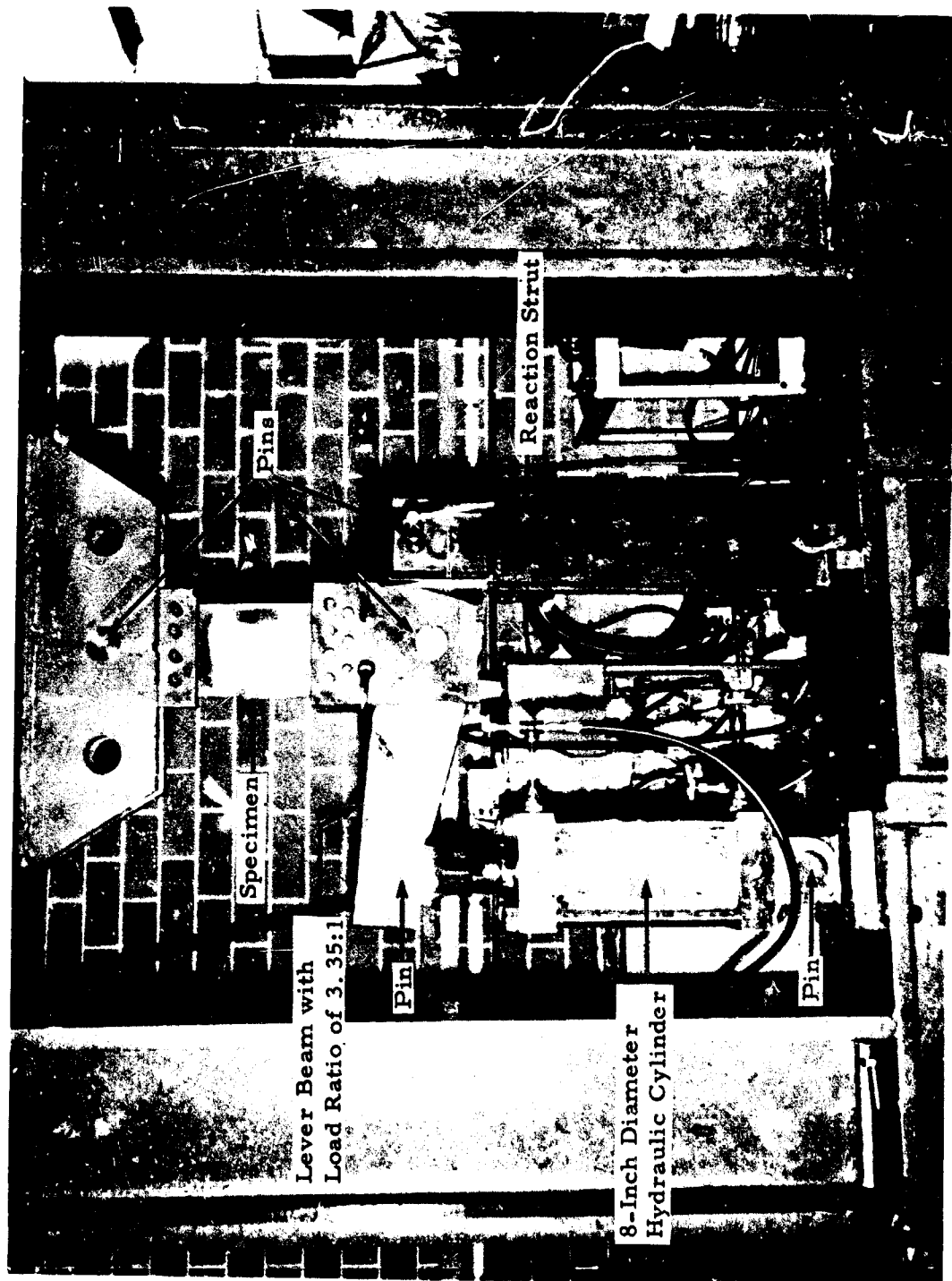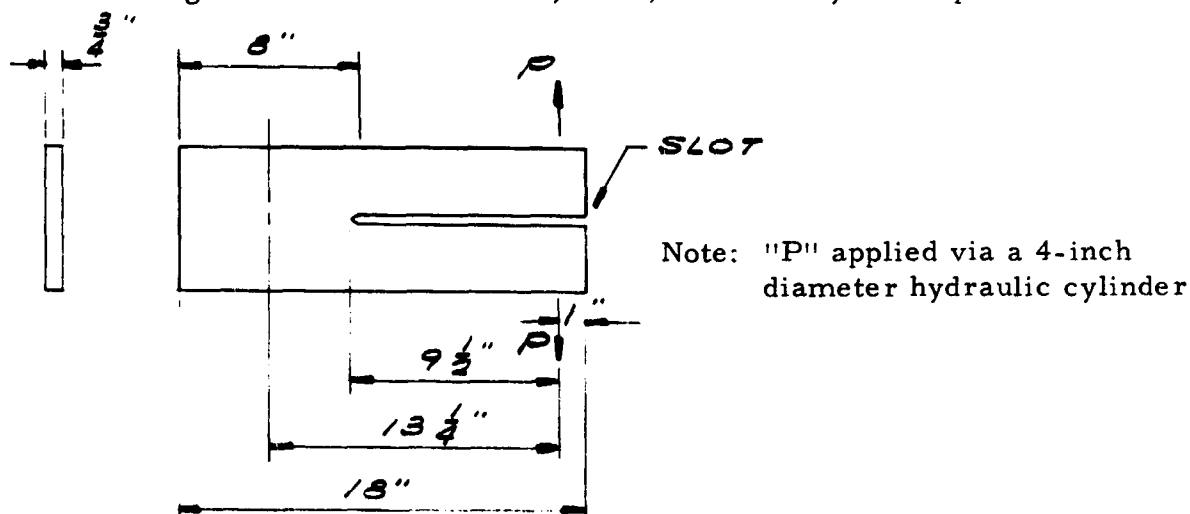
FIGURE 4. SPECIMEN CONFIGURATION "B"

FIGURE 5. THE LOADING FRAME WITH SPECIMEN INSTALLED

specimen was loaded as a two force member even though the lever beam and pin traveled in a circular arc.

Measurements during the course of testing were made by means of a 40x reticule mounted in a housing that could be clamped to he specimen. A grid, etched on the reticule, allowed measurement to the nearest quarter mil with reference to a line scribed at the end of the initial fatigue crack. During testing, measurements were taken at intervals ranging from one or two hundred to one or two thousand cycles depending on the extent of crack growth that was visually apparent. Because the crack did not progress at exactly the same rate on both sides of the specimen, the extensions were read on both sides after the conclusion of each increment; stress intensity factor, K, was then calculated based on an average incremental growth.

IV.   DISCUSSION OF TEST RESULTS

As mentioned in the previous section, a fatigue crack was generated in a patch plate by means of a load applied via a hydraulic cylinder. As is shown below, these results, in themselves, provide useful information as to crack growth rates. Consider, first, a free body of the patch:

Note: "P" applied via a 4-inch diameter hydraulic cylinder

Initially, the cylinder was pressurized to 750 psi which induced a load of 7,620 lbs; stress normal to the tip of the saw cut then becomes:

$$\sigma \; = \; \frac{6M}{bt^2} \; + \; \frac{P}{A} \; = \; \frac{(6)(7620)(13.25)}{(3/4)(7.5)^2} \; + \; \frac{7620}{(3/4)(7.5)} \; = \; 15,725 \text{ psi}$$

The above stress was applied 1500 times and, as no crack was detectable upon inspection by dye penetrant, the hydraulic cylinder pressure was increased to 1,000 psi; this results in an applied load of 10,000 lbs and produces a stress normal to the flaw tip of 21,000 psi. Upon repeated application of this load, a fatigue crack initiated after approximately 200 cycles and grew to a length of 3/16-inch during the subsequent

300 cycles. The crack growth rate was therefore:

$$\frac{\Delta a}{\Delta N} \simeq \frac{0.188}{300} \simeq \underline{6.3 \times 10^{-4} \text{ inches/cycle}}$$

The ΔK range associated with the above may be calculated by considering that the patch plate geometry and loading is analogous to a semi-infinite notch in the free edge of a half plane. Then ΔK^{*} becomes:

$$\Delta K = \pi^{1/2} \left\{ \frac{4\pi - 12}{\pi^2 - 8} \right\} \frac{P}{tc^{1/2}} + \pi^{1/2} \left\{ \frac{4\pi - 8}{\pi^2 - 8} \right\} \frac{Pl}{tc^{1.5}}$$

$$= (1.77) \left\{ \frac{0.57}{1.87} \right\} \frac{(10,000)}{(0.75)(2.78)} + (1.77) \left\{ \frac{4.57}{1.87} \right\} \frac{(10,000)(13.75)}{(0.75)(20.5)}$$

$$= 2590 + 38,700 \simeq \underline{41 \text{ ksi}\sqrt{\text{in}}}$$

After growth of the fatigue crack(s), and welding-in of the patch plate(s), testing was performed at various ΔK ranges for both specimen configurations. For computing stress intensity for these tests, however, the formula used was $\Delta K = 1.12 \, \sigma\sqrt{\pi a}$. This is the generally accepted relationship for the case of an edge notch in a semi-infinite plate subjected to axial tension. The results are shown in Figure 6, but it will be noted therein that the ΔK ordinate and $\Delta a/\Delta N$ abscissa computed for the case of growing the initial fatigue crack does not agree with the balance of the test data. No explanation for this disparity is readily apparent.

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*See "Stress Analysis of Cracks," P. C. Paris and G. C. Sih, ASTM STP No. 381.

V. CONCLUSIONS

The results of the tests conducted in this investigation indicate that, as might be expected for a given stress intensity range, crack growth rate is accelerated by the presence of high residual stresses normal to the tip of a fatigue crack. The equation for the rate of growth may be determined from the data of Figure 6. Therein:

$\Delta K = AR^M$ where $R = \Delta a / \Delta N$ and "A" and "M" are constants.

For the case of the "as-received" plate:

M = slope of the log-log curve, viz., 0.225

Also, when $\Delta K = 150$, $R = 10^{-3}$

$\therefore \Delta K = A(10^{-3})^{0.225} = \dfrac{A}{10^{0.675}} = 150$

and $A = (150)(4.732) = 709.8$

$\therefore \Delta K = 709.8 R^{0.225}$ or,

$R = \dfrac{\Delta a}{\Delta N} = \dfrac{\Delta K^{4.44}}{4.561}(10^{-12}) = \underline{\underline{(219)(10^{-15})\,\Delta K^{4.44}}}$

For the case of the intentionally induced residual stress:

$M = 0.174$ and,

When $\Delta K = 77$, $R = 10^{-3}$

$\therefore \Delta K = A(10^{-3})^{0.174} = \dfrac{A}{10^{0.522}} = 77$

and $A = (77)(3.327) = 256.2$
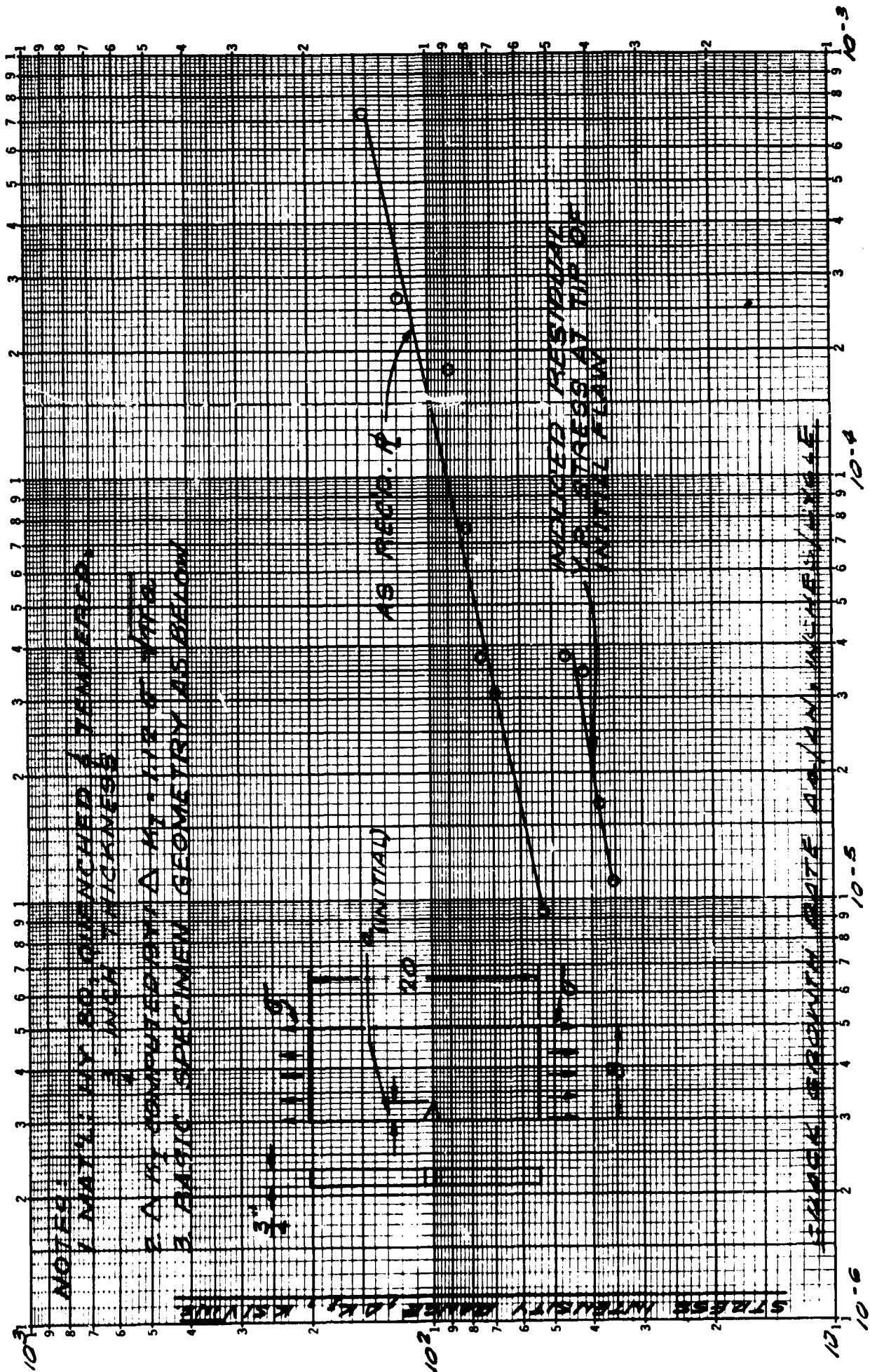
$\therefore \Delta K = 256.2 R^{0.174}$ or,

FIGURE 6. CRACK GROWTH RATE VS STRESS INTENSITY RANGE -
HY-80 STEEL

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$$R = \frac{\Delta a}{\Delta N} = \frac{\Delta K^{5.75}}{70.69} \times 10^{-12} = \underline{(14.1)(10^{-15}) \Delta K^{5.75}}$$

The latter, by inspection, results in the faster growth rate for any significant value of ΔK.
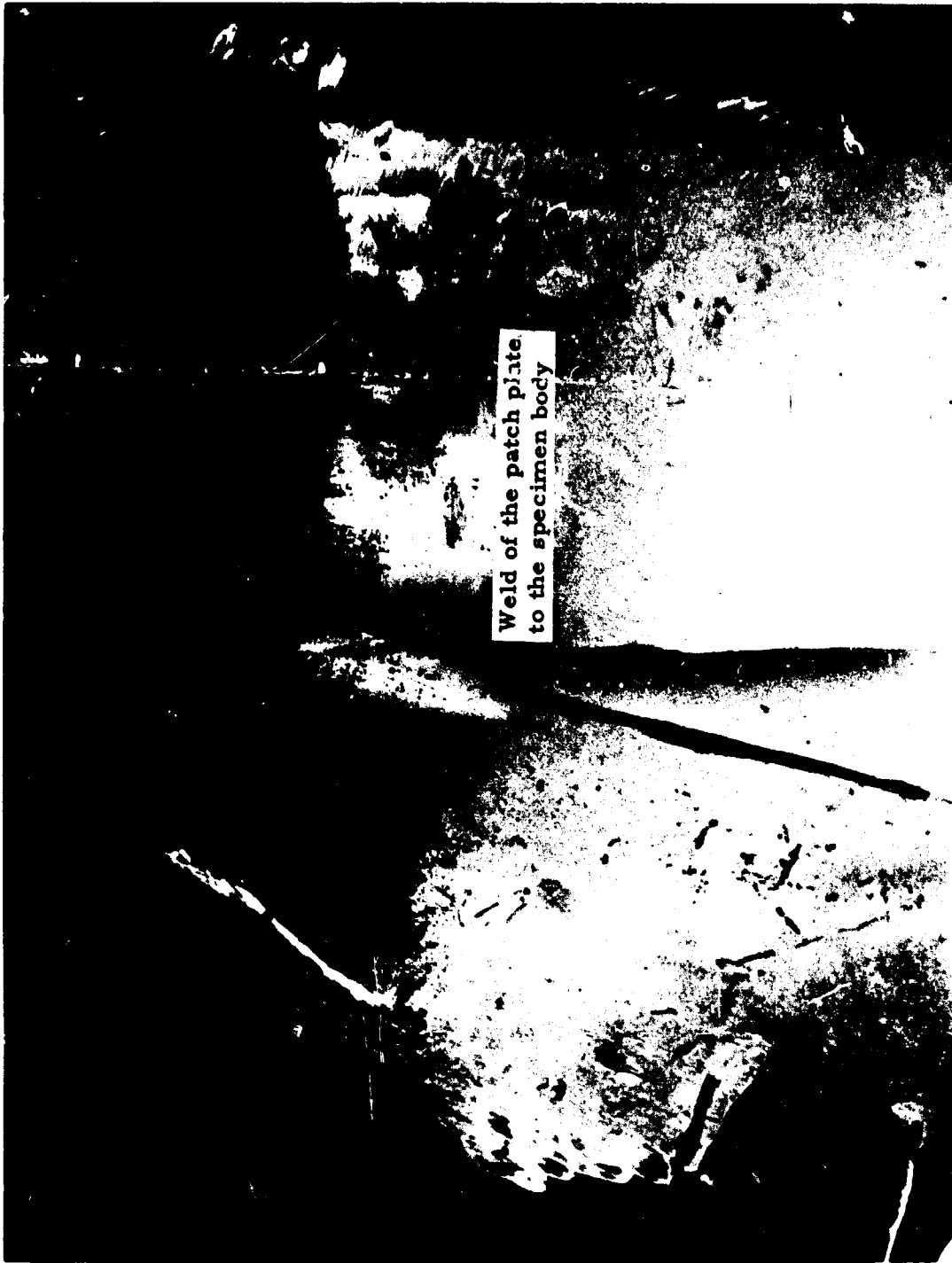
Typical photographs of failed specimens follow.

FIGURE 7. FINAL FAILURE OF A SPECIMEN WITH NO WELD-INDUCED RESIDUAL STRESSES NEAR THE FATIGUE CRACK TIP

Weld of the patch plate to the specimen body

FIGURE 8. FINAL FAILURE OF A SPECIMEN WITH WELD-INDUCED Y. P. RESIDUAL STRESSES ACROSS THE FATIGUE CRACK TIP